LCA Case Studies

The Application of the Environmental Product Declaration to Waste Disposal in a Sanitary Landfill

Four Case Studies

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Abstract

Goal, Scope and Background. The aim of the present study is to evaluate, through LCA, the potential environmental impact associated to urban waste dumping in a sanitary landfill for four case studies and to compare different technologies for waste treatment and leachate or biogas management in the framework of the EPD® system. Specific data were collected on the four Italian landfills during a five-year campaign from 2000 to 2004. This work also analyses the comparability of EPD results for different products in the same product category. For this purpose, a critical review of PSR 2003:3, for preparing an EPD on 'Collection, transfer and disposal service for urban waste in sanitary landfills', is performed.

Methods. PSR 2003:3 defines the requirements, based on environmental parameters, that should be considered in an LCA study for collecting and disposal service of Municipal Solid Waste (MSW) in a sanitary landfill. It defines functional unit, system boundaries towards nature, other technical systems and boundaries in time, cut-off rules, allocation rules and parameters to be declared in the EPD. This PSR is tested on four case studies representing the major landfills located from the farthest west to the farthest east side of the Ligurian Region. Those landfills are managed with different technologies as concerns waste pretreatment and leachate or biogas treatment. For each landfill, a life cycle assessment study is performed.

Results and Discussion. The comparison of the LCA results is performed separately for the following phases: transport, landfill, leachate and biogas. The following parameters are considered: Resource use (Use of non-renewable resources with and without energy content, Use of renewable resources with and without energy content, Water consumption); Pollutant emissions expressed as potential environmental impact (Global Warming Potential from biological and fossil sources, Acidification, Ozone depletion, Photochemical oxidant formation, Eutrophication, Land use, Hazardous and other Waste production). The comparison of the LCA results obtained for alternative landfill and biogas management techniques in the case studies investigated shows that the best practicable option that benefits the environment as a whole must be identified and chosen in the LCA context. For example, a strong waste pre-treatment causes a high biological GWP in the landfill phase, but a low GWP contribution in the biogas phase, due to the consequent low biogas production, evaluated for 30 years since landfill closure.

Conclusion. The analysis of four case studies showed that, through the EPD tool, it is possible to make a comparison among different declarations for the same product category only with some modification and integration to existent PSR 2003:3. Results showed that different products have different performances for phases and impact categories. It is not possible to identify the 'best product' from an environmental point of view, but it is possible to identify the product (or service) with the lowest impact on the environment for each impact category and resource use.

Recommendation and Perspective. In consequences of the verification of the comprehensiveness of existent PSR 2003:3 for the comparability of EPD, some modifications and integration to existent rules are suggested.

Keywords: Environmental Product Declaration (EPD); Italy; landfill, sanitary; Municipal Solid Waste (MSW); Product Category Rules (PCR); Product-Specific Requirements (PSR); specific rules, Type III label; waste disposal

Introduction

It's well known that Life Cycle Assessment (LCA) is an environmental management tool that enables quantification of environmental burdens and their potential impacts over the whole life cycle of a product, process or activity. Nowadays, LCA is widely used as a decision making tool, for example in a process selection, design and optimisation in order to identify clean technologies; furthermore, it's a tool that can also provide environmental information.

In the LCA-definition, the term 'product' includes not only product systems but also service systems [1], such as waste management systems. Therefore, LCA can help decision makers to find different strategies for a sustainable integrated solid waste management system: LCA assesses the potential environmental impact associated with waste treatment by considering resource depletion, air, water and land pollution in the full life cycle [2]. In order to adopt LCA in waste management, however, methodological choices and a number of aspects are required that still need to be worked out. Issues such as upstream and downstream system boundaries, open-loop recycling allocation, multi-input allocation and time-frame should be considered when LCAs are applied to solid waste management systems [3]. For example, if a too

short time period is chosen performing an analysis which includes landfilling processes, results and conclusions in an LCA may be misleading [3]. The definition of these methodological choices depends on the goal of the study [4].

Therefore, in order to be able to add up LCA-based information and to compare different LCA studies, common and harmonised calculation rules have to be established to ensure that similar procedures are used for data collection and handling. This applies, for instance, to goal and scope of the study, demands for data quality, assumptions done as well as the choice of calculation methods.

In the framework of the EPD® system, the official Type III environmental label, the comparability is guaranteed by PSR (Product-Specific Requirements, the term 'PCR' – Product Category Rules – is suggested in ISO CD 14025.1 [5] to replace the term PSR), since the information in the declarations are being collected and calculated based on common rules. For comparing EPDs on 'Collection, transfer and disposal service for urban waste in sanitary landfills', PSR 2003:3 [6] has been used.

Environmental Product Declaration represents a verifiable and accurate way to show the environmental aspects of products or services, viewed from a comprehensive life cycle perspective 'from cradle-to-grave'. It is defined as 'quantified environmental data for a product, with pre-determined parameters, based on the ISO 14040 [1] series of standards, which may be supplemented by other qualitative and quantitative information' [5]. The information contained in the EPD, developed using Life Cycle Assessment (LCA), are exclusively informational in nature, and the declaration contains no criteria for assessment, preferability or minimum levels to be met.

The aim of the present study is to evaluate, through LCA, the potential environmental impact associated to urban waste dumping in a sanitary landfill for four case studies and to compare different technologies for waste treatment and leachate or biogas management in the framework of the EPD® system. Specific data were collected on the four Italian landfills during a five-year campaign from 2000 to 2004. The four investigated sites represent the major landfills located in the Ligurian Region: in 2002 they received about 615,000 tons of waste, representing 70% of the total waste produced in Liguria. The similar waste composition, the wide spatial distribution along the Ligurian coast and the different technologies of managing the landfills, allow them to be considered as representative LCA case studies.

Through the application of the EPD tool to waste management, this work also analyses the comparability of EPD results for different products in the same product category. For this purpose, a critical review of PSR 2003:3 'Collection, transfer and disposal service for urban waste in sanitary landfills' is performed.

1 Methods

The PSR 2003:3 document was prepared by Department of Chemical and Process Engineering 'G.B. Bonino' (DICheP – University of Genoa), that performed an LCA study on collection, transfer and disposal service for urban waste in Val Bosca sanitary landfill, located in La Spezia Province (farthest east side of the Ligurian Region coast, north of Italy), managed by the ACAM SpA company [7,8]. The PSR 2003:3 document was then issued in an open and participatory process between companies and organisations having a good knowledge of the specific environmental aspects of the service to be included in the EPD® system.

PSR 2003:3 was applied to other three sanitary landfills during a five-year campaign from 2000 to 2004. These landfills (Collette Ozotto, Boscaccio, Scarpino) are respectively located on: the farthest west side (Imperia), west side (Savona) and central area (Genova) of the Ligurian Region coast. Liguria is a maritime region and it finds its most important economical factors in the activity of the ports and in that of tourism. Genova was one of the three major industrial cities in Italy for a long time. Nowadays, many factories have turned to other so-called tertiary sectors like commerce, communications, banking and other various types of services.

Liguria has 1,625,000 inhabitants split into 235 Municipalities (January, 2000). From an administrative point of view, the Region is split into four Provinces: Savona (SV) with 69 Municipalities, Imperia (IM) with 67, Genova (GE) with 67 and La Spezia (SP) with 32.

The three landfills are managed by Italian companies involved in waste management (Idroedil Srl, Ecosavona Srl, AMIU SpA) that decided, as ACAM SpA, to perform a global impact investigation successfully through a life cycle approach and environmental aspects communication by the EPD scheme. All these EPDs have been validated by the Certification Body RINA SpA. The four investigated landfills represent the major landfills located from the farthest west to the farthest east side in the Ligurian Region; they receive urban waste and they are managed with different technologies.

In **Table 1**, the waste composition of the four case studies are presented together with the average waste composition of the Ligurian Region (Regional Waste Managing Plan of Ligurian Region).

These values are quite different to each other, due to the fact that the data derives from different sampling plans, field data collection procedures, sorting procedures, and visual sampling procedures used in the various case studies.

Case studies I, III and IV waste compositions derived from solid waste characterisation studies conducted at the respective landfills. Instead, Case Study II's waste composition was derived from a household solid waste analysis conducted by the Imperia Province during the year 2000. When waste are characterised by direct sampling at final disposal sites, their composition refers to household solid waste mixed with other waste (inert material, …) that landfills are authorised to receive. As concerns case III, a so high value of 'Organic Fraction' included the 'Screened material' fraction.

In general, the major differences in the composition of waste disposed in the four landfills can be explained in terms of: a) the quick decomposition of putrescible materials, which become unidentifiable material over several months; b) the

Table 1: Composition of waste disposed in landfills and MSW average composition of Ligurian Region

Waste Composition (%)	Case I	Case II	Case III	Case IV	MSW Ligurian Average
Organic fraction	19.71	27.3	44.67	14.71	25
Paper/paperboard	27.01	26.3	21.6	37.33	23
Plastic material	19.51	9.8	16.06	15.65	9
Textiles	2.46	0	0	4.28	2
Wood	3.08	0	4.5	6.59	3
Metals	2.06	5.9	2	5.44	12
Glass	1.71	10.2	11.17	7.07	8
Screened material	24.46	20.5	0	8.93	18

addition of considerable amounts of cover and inert filling materials, and building/demolition debris at the final disposal sites; and c) the inclusion of materials that are not generated in households.

This point represents the major bottleneck of the studied system and should be better analysed in the PSR that should clearly define an univocal waste analysis methodology. The LCA results are in fact strongly dependent on waste composition: this parameter influences the evaluation of biogas produced, of biogas collecting efficiency, of waste calorific value and of emission from waste pre-treatment systems. Other values influenced by waste composition (for example, leachate quality and quantity) are usually derived from analytical sampling.

1.1 Site description

Case Study I. The LCA study was carried out for the service realised in Val Bosca landfill, situated about 1.5 km east of La Spezia (Italy). Waste transferring to Val Bosca started in 1998 at elevation 20 m above sea level. In the 1998–2002 period, 408,887 tons of waste had been disposed there.

Case Study II. Case study II regards the service realised in Collette Ozotto landfill. The site, located in Bussana hamlet of Sanremo, extends along a hillside strip near the ridge descending towards SSW from an elevation 385 to 420 m above sea level. Waste disposal started in 1975 on a hill descent 2 km distant from the coastline and 300 m above sea level. Since then, about 800,000 tons of waste have been disposed of in the period between 1975 and 1992, and 250,000 tons from 1997 up to today, for a total of 1,050,000 tons. Between 1992 and 1997 no waste was disposed, but only closure and environmental requalification interventions were carried on.

Case Study III. The LCA study for case study III is carried out for the service realised in a site located in the municipal area of Savona (Italy), in Boscaccio landfill, situated in the Valley of Segno, about 5 km north-west of the Municipality of Vado Ligure. Waste transferring to Boscaccio started in 1992 at an elevation of 374 m above sea level. In the 1992–2002 period, 645,826 tons of waste had been disposed of. In these years, the company managed an increasing amount of waste, starting from a minimal quantity of 30,000 t/year, up to 100,000 t/year.

Case Study IV. Case study IV refers to Scarpino landfill, built in 1968 above a 400,000 m² area on the hills of Genoa. This area is bounded by the watershed of a valley, along the bottom of which the Cassinelle stream flows. Disposal started at an elevation of 590 m above sea level. This part of the landfill is exhausted as regards conferred volumes (5,529,968 t of waste, corresponding to about 7,000,000 m³) since 1995 and it's an area subdued to environmental remediation since the early nineties. Meanwhile, another site has been set for waste disposal, downhill from the original one. In this site, wastes are disposed between the two sides of the mountain using a disposal technique through terraces. Here, in the 1995–2002 period, about 3,200,000 tons of waste have been conferred.

1.2 Transport phase

The collection of waste represents a key part of waste treatment. There are big variations depending on the type of waste, especially with sorted special waste streams. Key parameters for collection are [9]: truck fuel consumption per km and loading capacity; distance to waste treatment location; population density. Therefore, the modellisation of waste collection and transfer is influenced by road configuration, by the presence of the integrated waste management system and by data availability. The latter point includes routes of trucks, oil consumption and % used of the maximum capacity of a truck. These data are very difficult to collect, especially when waste collection and transport is performed by different companies from the one managing the landfill (Case II and III).Therefore, a comparison of results should not be representative, due to the diversity of data collection methods [10]. This matter can be solved excluding the transport phase from this PSR. Otherwise, a corrective factor can be defined and applied to collected data when site-specific data cannot be obtained and average distances from municipalities to landfills are used.

In the present study, the transport phase is not included in the comparison. However, the impact related to transport is calculated using the following rules. For waste collection from litter bins, average data per hour were used for trucks during stationary use. Data are valid for engines under continuous changing loads [11]. The real capacity of a litter bin (i.e. about 80% of the maximum capacity) is used. For waste transfer to landfills, site-specific data derived from effective routes of trucks were used (Case I). If this information can't be obtained, this impact is calculated with the average distance from municipalities to landfill (Cases II and III). In the

actual modelling, these transports are assumed to have empty returns (70% of the full-truck impact) [12]. For case study IV, both waste collection and transfer impacts were calculated by fuel consumed by waste collecting and transferring trucks. The latter method seems the most reliable due to the accuracy of the collected data. Important causes of variation for energy intensity per km, in fact, are the size and utilisation of the vehicle: the influence of load depends on the load size, weight/volume ratio and return trip load. Inventory data for transportation systems expressed per litre of diesel used allows one to consider all these aspects.

1.3 Landfill phase

Landfill management is described as the set of the operations, carried out in the landfill, necessary to provide the waste disposal service, and the set of consumption and emissions generated by the same operations. Landfill management also includes landfill construction (excavation of the site and its preparation) and landfill post-closure operations (site remediation and environmental requalification of landfill).

To date, the Italian approach towards waste management has mainly been piecemeal and geared towards short-term solutions. Only in 1997 did the Italian state with the legislative decree n.22/97 (Decreto Ronchi) transpose the Waste Directive (1991) and the EU Packaging and Packaging Waste Directive (1994) into national law, grasping the opportunity of introducing major changes into its system for waste disposal and management. One of the salient features of the Decreto Ronchi is that, from the year 2000, landfilling will only be acceptable as a disposal option for inert waste and treated residues. This imposed stricter controls to waste sent to landfill, in particular biodegradable waste, and caused changes in waste management, including waste dry-wet separation and biological treatment of the organic material before its dumping. As above, in some of the considered case studies, waste pre-treatments occur after waste weighting and before their conferring on the 'dumping front'. Here, waste or their treated residues are compacted and covered with an inert, recovered material layer or with topsoil, about 20 cm thick, in order to limit the waste surface exposure to the atmosphere, to minimise possible odour emissions and to set up a suitable foundation for vehicle transit.

Site-specific data, representing annual average values for a specific year, were used for landfill management. Databank data were used for landfill construction [13], because of data lacking especially for older landfills. Design estimation is used for post-closure data. For case study II, as concerns post-closure, only daily covering is included because of lacking data.

Case Study I. Landfill management includes the operations carried out in the landfill. The daily collected wastes are unloaded in an area of the landfill body and shredded in order to support an aerobic bio-stabilisation process. Shredded waste are grounded and irrigated with a suspension of active biological substrate and, within the body of the landfill, used to build up piles. The piles are then covered over with a permeable to air covering, allowing ventilation, and impregnated with active carbon that acts as a barrier against odours. In order to accelerate the bio-stabilisation process within the piles, air is blown in, reaching temperature values above 50–55°C. The stabilisation process takes 7 days and, at the end of this period, the treated material is distributed throughout the landfill body. In this phase, machinery is used to compact and cover waste with sheets and/ or inert materials.

Case Study II. Landfill management includes the operations carried out in a transfer station and in the landfill. The daily procedure of landfill management includes the preventive separation of the organic fraction of waste and other materials by grinding and subsequent screening. The organic fraction can therefore be recovered and subsequently biostabilised in biocells (aerobic composting), and, on the other hand, the dry fraction can be disposed in the landfill. The organic fraction, after stabilisation, is dumped in the landfill.

Case Study III. Landfill management includes the operations carried out in the landfill. In this case study, no waste pretreatments occur.

Case Study IV. As in case study II, landfill management includes the operations carried out in two transfer stations and in the landfill. Nowadays, no waste pre-treatments occur.

1.4 Leachate phase

Leachate production, associated with landfilling a ton of waste, is modelled for a period of 30 years since landfill closure. Leachate produced, collected and dispersed are considered. Quantity, quality and depuration efficiency of the leachate produced are evaluated as a function of the landfill age [14]. Site-specific data are used for transport of leachate to external plant, when it occurs (case study I and II). When leachate is treated in external plant, databank data are used (case study I and II): the consumption of energy and the production of sludge for leachate biological treatments are assumed to be equal to 0.00033kWh/l and 1/10 of treated leachate. Otherwise, if leachate is treated on site, site-specific data are used (case study I).

Case Study I. The leachate produced in the landfill is collected and conveyed by various extraction systems with perforated pipes situated on the bottom and side walls of the collecting tank for the landfill drainage. The conveyed leachate is sent to storage tanks on site and it is then treated in the Reverse Osmosis (R.O.) and Ultrafiltration depuration plant located in the same building as the tanks. This plant has a rated capability of 2 m^3/h. 90–99% of inorganic leachate and organic compounds are removed by R.O. At the end of the process, there are three different streams: a solid stream (sludge) that is recycled in the landfill, a concentrated stream containing impurities which must be removed, and a depurated, permeate stream. The exceeding leachate and the concentrate stream are sent to different wastewater treatment plants. In these plants, leachate and permeate, together with wastewater, are biologically treated by active sludges with microorganisms able to reduce the amount of pollutants in the wastewaters, thanks to their biological activity.

Case Study II. In the last years, in Collette Ozotto, a small leachate production occurred in the various landfill lots, thanks to the poor rainfall and the high evapotranspiration. A better leachate control has been accomplished thanks to the landfill zoning into distinct lots separated by a natural rocky trench. The produced leachate is stored in 2 open tanks, each one with a capability of 80 m^3, by gravity accumulation. Part of the leachate is recycled in the landfill, and part of it is sent to biological treatment in authorised wastewater treatment plants.

Case Study III. Leachate is collected in two storage tanks with capabilities of 100 m^3 and 400 m^3. Each tank is provided with a lift station for leachate recycling on landfill body. Using perforated pipes, wastes in the landfill body are sub-irrigated. This operation has a twofold function: it leads to better waste compacting and it supports the waste fermentation process, speeding up digestion of the present organic fraction. Exceeding leachate is discharged in a sewer system.

Case Study IV. Leachate produced in the landfill is drained on the landfill bottom and sides by a complete perforated pipe system, made with HDPE, allowing one to keep the leachate head under the requested limits necessary and to assure the stability of waste covering. These pipes are collected to the landfill bottom, where leachate is stored in two tanks with about an 8,000 m^3 capability. The leachate micro-blister aeration plant is placed in the area upside to the storage tanks. It provides leachate degassing before its inflow into the sewerage system. At the moment, a tract of manifold that will lead the leachate to the depuration plant is under construction.

1.5 Biogas phase

Biogas production, associated with landfilling a ton of waste, is modelled for a time period of 30 years after landfill closure, as in the leachate phase. Biogas direct impacts are mainly due to the following contributions: biogas lost in the atmosphere and combustion emissions from flares or energy recovery plants. In order to evaluate the first contribution, it's necessary to forecast biogas and methane production with time using landfill gas generation models. In all case studies, predictions were made concerning the type of mathematical models which start from the amount of waste disposed of in a landfill and their composition [15]. These models are variations on first-order decay models that predict methane generation from a single batch of waste, which corresponds to the amount of MSW disposed of in a year. The models represent a landfill by a sequence of discrete batches, and the total gas generation at any point in time is the sum of the contribution from each batch. The models also include lag time between waste placement and commencement of gas generation, and also include an initial period of increasing gas production, prior to the onset of exponential decline in gas production [16]. A reaction representing the overall methane fermentation process for organics in solid waste can be represented by **Eq. (1)**:

$$C_aH_bO_cN_d + nH_2O \rightarrow xCH_4 + yCO_2 + wNH_3 + zC_5H_7O_2N + \text{energy} \tag{1}$$

where $C_aH_bO_cN_d$ is the empirical chemical formulation for biodegradable organics in solid waste, and $C_5H_7O_2N$ is the chemical formulation of bacterial cells. The biodegradable organic carbon found in MSW is transformed during anaerobic degradation into methane and carbon dioxide. The elementary composition of the waste is evaluated by the chemical composition of the materials listed in Table 1 [13].Once the elementary composition of the waste is known, this equation permits evaluation of both the quantity and the quality of the gas (CH_4 + CO_2) generation, neglecting the cell conversion of organic matter. All the previous calculations have been based on the amount of organic matter in the waste, considering its effective biodegradability evaluating the content of biodegradable organic carbon. Moreover, for each biogasifiable component of waste, its own degradation rate is considered in the model: the substrates are divided into three (slowly, moderately and readily biodegradable) classes [15]. In all case studies, the models are used to estimate the maximum theoretical yield of gas emission from landfills. The difference between the estimated generation rates for 30 years after landfill closure and the actual biogas collection rate at the landfills, derived from site-specific data and supposed constant in time, represents the quantity of biogas lost in the atmosphere in the time period considered. Biogas collection efficiency for a specific year is also evaluated from this difference. Site-specific data representing annual average values for a specific year are used for the evaluation of the quantity of biogas burned and then of combustion rate and composition. When available, site-specific data are used for biogas quality.

Therefore, waste composition and, in particular, their organic fraction, influenced the evaluation of biogas maximum yield and the evaluation of its collection efficiency.

Case Study I. The biogas is collected by 38 biogas extraction wells, plus 4 wells relating to the landfill development (when landfill bodies will be close to the foreseen plan to start the construction). The collected biogas is sent to 2 engines for energy recovery. Exceeding biogas is burnt on site in two flares with a total rated capability of 640 Nm^3/h. In 2002, 22% of collected biogas was sent to the engines for a production of 3,117,619 kWh, equivalent to 2 kWh/Nm^3. Nowadays, the estimated biogas collection efficiency is 92%. This value is obtained by creating negative pressure, or suction, to suck the gas from the landfill wells.

Case Study II. Nowadays, the biogas produced by the landfill is collected by vertical wells which are interconnected with a pipeline conveying it to a flare with a flow of 240 Nm^3/h. The estimated biogas collection efficiency is 70%. Up to now, no energy recovery has been performed.

Case Study III. The biogas produced by the biological processes that occur in the landfill is collected by 32 biogas extraction wells, linked in groups to biogas sub-stations, acting as regulators of a collecting process. The collected biogas is sent to 4 engines (3 engines with 330kW power and one with 240 kW power) for energy recovery (electric) from biogas. If the cogeneration plant stops, the collected biogas is automatically sent to a flare. This flare operates as a safety valve of the whole plant. In 2002, it operated for about 67 hours. In 2002, 98.8% of collected biogas was sent to the

engines, for a resulting production of 6,235,107 kWh, corresponding to 1.55 kWh/Nm³. The estimated biogas collection efficiency is 70%.

Case Study IV. At the end of 2002, 22 biogas extraction wells were installed; afterwards, in 2003, another 26 wells started to operate; the biogas produced is collected and sent to two flares (both of them built in 1997), with nominal flows of 1,000 and 1,500 Nm³/h. In 2002, the average hourly flow of burnt biogas was 160 Nm³/h, corresponding to an estimated biogas collection efficiency of 11%. We should consider that the biogas extraction plant became operative in 1997, in that landfill zone working since 1968 and exhausted in 1995. Consequently, the low collection efficiency was due to the distant disposal era and to the dumping methods used in that period, not suited to support an anaerobic environment typical of the methanogen period of the waste. In 2003, with the activation of new extraction wells, collection efficiency increased to 27%. Nevertheless, 2002 data are used for the comparison.

2 Results and Discussion

2.1 Resource use

Tables 2, 3 and 4 show Non-Renewable and Renewable Resource Use, Electricity Net Consumption and Water Consumption of service providing for 1,000 kg of waste. Resources using calculations include feedstock energy, including waste feedstock energy, i.e. energy potentially recoverable by waste, obtained from its calorific value. The Electricity Net Consumption represents the quantity of electricity used in the system studied. Non-Renewable Resource Without Energy Content consumption, meaningful only in the landfill phase, are comparable for Case I and in Case IV. In Case II, the total value is very low because no post-closure management was considered. On the other hand, resource consumption in Case III is very high due to the big amount of topsoil that is used. In the leachate phase, resource consumption is due to leachate transport and treatment. Non-Renewable Resource With Energy Content consumption with oil at a higher contribution, are comparable for all case studies regarding the landfill phase. In leachate and biogas phases, Case III demonstrates the lowest resource consumption values and water consumption, due to the low electricity consumption to convey biogas to the cogeneration plant in respect to flames and to recycle leachate to the landfill body. In Renewable Resource With Energy Content consumption, the higher contribution is given by waste calorific values, calculated by waste composition. Electricity consumption for all case studies is proportional to resource with energy content consumption. In Case II, in the leachate phase, electricity consumption is included in the landfill phase due to the difficulty of allocation.

Table 2: Resource use: landfill phase

Resource use	Landfill			
	Case I	Case II	Case III	Case IV
Non-Renewable Resource Without Energy Content	kg/t	kg/t	kg/t	kg/t
Clay	332.4213	<0.0001	30.0743	44.4605
Limestone ($CaCO_3$)	7.0600	7.0574	7.0621	2.6189
Gravel	89.6107	8.5013	33.5014	87.6089
Topsoil	101.2074	–	1 163.2740	479.01053
Other				
TOTAL	**530.8295**	**16.1854**	**1 234.4556**	**613.9896**
Non-Renewable Resource With Energy Content	MJ/t	MJ/t	MJ/t	MJ/t
Coal	21.9988	19.5635	21.6123	21.8365
Oil	188.1471	244.6928	179.0891	243.7473
Gas	27.3770	35.0149	35.7333	40.5212
Nuclear	12.6344	12.1563	13.5441	16.7630
Sulphur	0.0044	0.0036	0.0045	0.0048
Hydrogen	0.0869	0.0778	0.0803	0.0366
Peat	0.0039	0.0017	0.0020	0.0019
Lignite	0.1151	0.3966	0.4117	0.5940
TOTAL	**250.3674**	**311.9073**	**250.4773**	**323.5052**
Renewable Resource With Energy Content	MJ/t	MJ/t	MJ/t	MJ/t
Hydroelectric	1.7877	7.6426	7.9347	12.0605
Wood	0.2081	0.2081	0.2081	0.0766
Biomass	10 262.7	7 194.6908	8 024.9	10 518.0
Geothermic	0.0538	0.3775	0.3912	0.6298
Wave/tidal	0.0010	0.0037	0.0039	0.0061
TOTAL	**10 264.8**	**7 202.9**	**8 033.5**	**10 530.8**
Total Water Consumption kg/t	**351.6980**	**238.1600**	**201.8968**	**192.0718**
Electricity Net Consumption MJ/t	**3.5511**	**24.9246**	**25.8273**	**41.57441**
Produced electricity MJ/t	–	–	–	–

Table 3: Resource use: leachate phase

Resource use	Leachate			
	Case I	Case II	Case III	Case IV
Non-Renewable Resource Without Energy Content	kg/t	kg/t	kg/t	kg/t
Clay	–	–	–	–
Limestone ($CaCO_3$)	3.3836	0.0343	–	–
Gravel	–	–	–	–
Topsoil	–	–	–	–
Other				
TOTAL	**4.4930**	**0.2350**	**<0.0001**	**0.0002**
Non-Renewable Resource With Energy Content	MJ/t	MJ/t	MJ/t	MJ/t
Coal	5.2480	3.6633	0.0424	5.9921
Oil	34.8335	118.4100	0.1829	25.8421
Gas	32.8666	4.4508	0.0853	12.0539
Nuclear	4.1214	0.8699	0.0408	5.7666
Sulphur	1.6060	0.0059	<0.0001	<0.0001
Hydrogen	0.0670	0.0058	<0.0001	<0.0001
Peat	0.0007	0.0002	<0.0001	<0.0001
Lignite	0.3052	0.0065	0.0017	0.2434
TOTAL	**79.0485**	**127.4125**	**0.3532**	**49.8981**
Renewable Resource With Energy Content	MJ/t	MJ/t	MJ/t	MJ/t
Hydroelectric	2.1211	0.0580	0.0358	5.0621
Wood	<0.0001	<0.0001	<0.0001	<0.0001
Biomass	0.0597	0.0023	0.0010	0.1354
Geothermic	0.1098	0.0014	0.0019	0.2707
Wave/tidal	0.0011	< 0.0001	<0.0001	0.0025
TOTAL	**2.2918**	**0.0618**	**0.0387**	**5.4709**
Total Water Consumption kg/t	**17.3671**	**8.5763**	**0.0104**	**1.4740**
Electricity Net Consumption MJ/t	**6.9392**	–	**0.1163**	**3.85969**
Produced electricity MJ/t	–	–	–	–

Table 4: Resource use: biogas phase

Resource use	Biogas			
	Case I	Case II	Case III	Case IV
Non-Renewable Resource Without Energy Content	kg/t	kg/t	kg/t	kg/t
Clay	–	–	–	–
Limestone ($CaCO_3$)	–	–	–	–
Gravel	–	–	–	–
Topsoil	–	–	–	–
Other				
TOTAL	**<0.0001**	**0.0001**	**<0.0001**	**<0.0001**
Non-Renewable Resource With Energy Content	MJ/t	MJ/t	MJ/t	MJ/t
Coal	1.8129	2.3607	0.0347	0.9900
Oil	7.8187	10.1811	0.1470	4.2697
Gas	3.6470	4.7489	0.0686	1.9916
Nuclear	1.7447	2.2719	0.0328	0.9528
Sulphur	<0.0001	<0.0001	<0.0001	<0.0001
Hydrogen	<0.0001	<0.0001	<0.0001	<0.0001
Peat	<0.0001	<0.0001	<0.0001	<0.0001
Lignite	0.0737	0.0959	0.0014	0.0402
TOTAL	**15.0969**	**19.6585**	**0.2838**	**8.2433**
Renewable Resource With Energy Content	MJ/t	MJ/t	MJ/t	MJ/t
Hydroelectric	1.5316	1.9943	0.0288	0.8364
Wood	<0.0001	<0.0001	<0.0001	<0.0001
Biomass	0.0410	0.0533	0.0008	0.0224
Geothermic	0.0819	0.1067	0.0015	0.0447
Wave/tidal	0.0008	0.0010	<0.0001	0.0004
TOTAL	**1.6552**	**2.155**	**0.0311**	**0.9039**
Total Water Consumption kg/t	**0.4459**	**0.5807**	**0.0084**	**0.2435**
Electricity Net Consumption MJ/t	**4.2825**	**7.0417**	**0.1196**	**2.00677**
Produced electricity MJ/t	**32.5662**	–	**497.0853**	–

2.2 Pollutant emissions

Tables 5, 6 and 7 show the emissions, expressed as environmental potential impacts, which occur during service providing for 1,000 kg of waste and the generation of waste, classified as hazardous waste and other waste, during service providing for 1,000 kg of waste. In the calculation of kg CO_2-equivalents, the contribution of biological C (present in bio-stabilisation emissions, CO_2, and in the biogas that is not collected, CO_2 and CH_4) has been distinguished from the non-biological case. The amount derived from exhaust gases emitted by the flare and by the energy recovery plant (biogas phase) is included in the non-biological GWP. Only hazardous wastes produced in the plant are considered (Landfill phase). As concerns biological GWP100 for the landfill phase, Case I and II present a contribution due to waste pre-treatments (**Fig. 1**). Non-biological contribution is due to waste compacting by diesel machinery. A strong waste pre-treatment and a higher biogas collection efficiency, evaluated for 30 years after landfill closure, cause a low biogas production and then a low GWP100 contribution in

Table 5: Pollutant emissions: landfill phase

Category of Impact	Unit	Landfill			
		Case I	Case II	Case III	Case IV
GWP100 – biological sources – non-biological sources	 kg CO_2 kg CO_2	 37.80 16.19	 7.66 20.93	 – 15.78	 – 21.98
AP	mol H^+	8.17	10.51	7.99	11.67
POCP	kg C_2H_4	0.03022	0.00839	0.03566	0.05270
EP	kg O_2	0.97665	1.27693	0.83274	1.24332
ODP	kg CFC11	0.00000004	0.00000003	0.00000003	0.000000023
Land Use	$m^2 \cdot$year	0.4092	1.1840	0.2957	2.26681
Hazardous Waste	kg/t	0.01590	0.01572	0.1116	0.134566
Other waste	kg/t	283.0120	4.4315	25.3793	40.9561

Table 6: Pollutant emissions: leachate phase

Category of Impact	Unit	Leachate			
		Case I	Case II	Case III	Case IV
GWP100 – biological sources – non-biological sources	 kg CO_2 kg CO_2	 – 5.95	 – 9.18	 – 0.02	 – 3.02
AP	mol H^+	2.48	4.36	0.01	2.03
POCP	kg C_2H_4	0.00651	0.000183	0.00006	0.00791
EP	kg O_2	1.04832	1.00452	0.51685	84.9528
ODP	kg CFC11	0.00000004	0	0	0
Land Use	$m^2 \cdot$year	–	–	–	–
Hazardous Waste	kg/t	–	–	–	–
Other waste	kg/t	7.5085	7.8588	7.1158	0.0575

Table 7: Pollutant emissions: biogas phase

Category of Impact	Unit	Biogas			
		Case I	Case II	Case III	Case IV
GWP100 – biological sources – non-biological sources	 kg CO_2 kg CO_2	 69.51 173.04	 121.39 74.43	 263.84 403.53	 1 526.83 13.83
AP	mol H^+	5.31	4.32	22.32	4.14
POCP	kg C_2H_4	0.00813	0.00136	0.00102	0.00164
EP	kg O_2	0.85916	0.59281	3.98412	0.35030
ODP	kg CFC11	0	0	0	0
Land Use	$m^2 \cdot$year	–	–	–	–
Hazardous Waste	kg/t	–	–	–	–
Other waste	kg/t	0.0174	0.0227	0.0003	0.0095

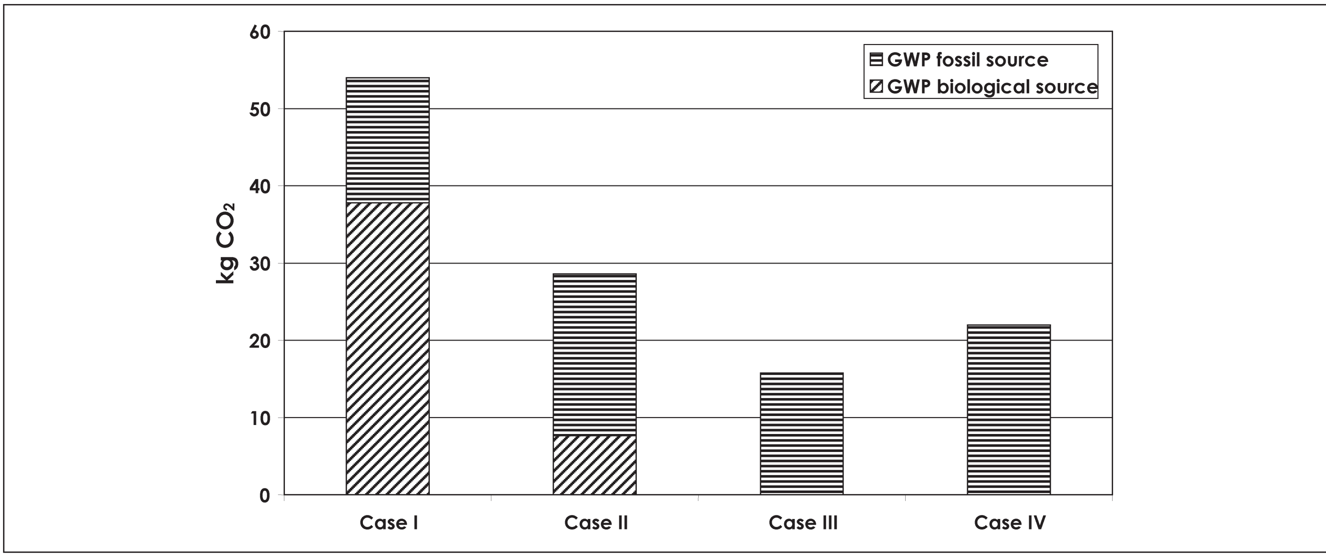

Fig. 1: GWP100 landfill phase

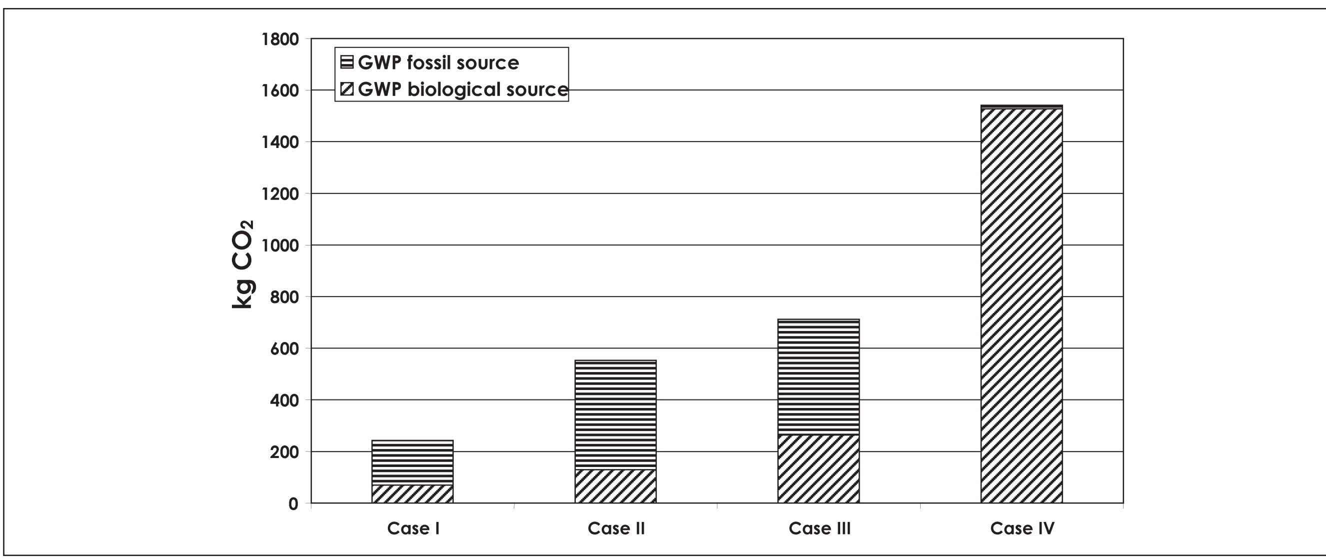

Fig. 2: GWP100 biogas phase

the biogas phase (**Fig. 2**). The biogas production was calculated for 30 years after landfill closure as a function of waste composition and biogas collection efficiency. As concerns the biogas phase, Case III presents a high GWP100 value due to the high content of Organic material (see Table 1). In the biogas phase, the biological source involves only biogas that is not collected. Non-biological GWP100 includes exhaust gases emitted by flares and energy recovery plant instead. Obviously a higher biogas production causes a higher GWP contribution. As concerns Case IV, about 30% of GWP100 of the biogas phase due to biological sources refers to the period from 1968 to 1997 and regards the older site of the landfill. As concerns AP, potential environmental impact is similar for all cases. Only Case III presents the lowest value for leachate phase and the highest for the biogas phase, due to the leachate recycling and to the highest biogas production. POCP is principally due to hydrocarbon emission, from machineries composting waste, from leachate transport and from diesel production. EP, significant only for the leachate phase, is comparable for case studies I, II and III, where leachate is treated with ultrafiltration and reverse osmosis, by biological activity in a wastewater treatment plant, or recycled on a landfill body. The absence of any treatment on leachate produced by Case IV landfill causes such a high EP value. Regarding ODP, CFC emission is due to HDPE production in the landfill phase and LDPE resin production as a reactant for R.O. leachate treatment in the leachate phase for Case I. As concerns Land use, evaluated in landfill phase as 'Land occupation impacts', Case II and IV present a high value due to the age of those landfills and then to a significant contribution of 'time' in Equation (1). Through this approach, it came out that the old landfills are penalised. PSR can state that Land use has to be evaluated only as 'Land change' and expressed in m^2·years·quality difference.

The comparison of the LCA results obtained for the alternative waste treatment method and biogas management in the investigated landfills, i.e. the application of LCA to process selection, shows that the best practicable option that benefits the environment as a whole must be identified and chosen in the LCA context. However, the best practicable option has to be determined on a case-by-case basis and LCA results are strongly dependent on the boundaries, operating state of the system and on the economic system in which it operates.

3 Conclusion

Nowadays, in the waste management field, there is an increasing demand of LCA-based, so-called Type III environmental declarations from policy makers and citizens. As concerns EPDs applied to waste treatment services, they should be used as a source of information by citizens, municipalities, local corporations and industrial consumers enabling one to add up and accumulate LCA-based data in the supply chain and to provide easily accessible, quality-assured and comparable information regarding environmental performance of these kind of services [8,17]. Life-cycle approach applied to the major companies performing waste treatment in the Ligurian area, shows that LCA represents an environmental management tool able both to communicate environmental information by the Type III environmental label EPD, and to look for different scenarios that can improve the environmental performance of the 'Collection, transfer and disposal service for urban waste in sanitary landfill'. The analysis of four case studies showed that it is possible to make a comparison among different EPDs for the same product category only with some modification and integration to existent PSR 2003:3. The results obtained, as concerns the 'biogas phase', strongly depend on waste composition and, in particular, from the evaluation of the organic fraction of waste.

Instead, the comparison of landfill and leachate results among different EPDs, makes it possible to use the actual rules defined by the existent PSR 2003:3.

In general, results showed that different products have different performances for phases and impact categories. It is not possible to identify the 'best product' from an environmental point of view, but it is possible to identify the product (or service) with the lowest impact on the environment for each impact category and resource use.

4 Recommendation and Perspective

An objective of the present paper was also to verify the comprehensiveness of existent PSR 2003:3 for the comparability of EPD and to identify main modification and integration to existent rules. The following modifications can be suggested:

- PSR should clearly define an univocal waste analysis methodology.
- PSR can state that Land use has to be evaluated only as 'Land change' and expressed in m^2·years·quality difference.
- PSR can exclude the transport phase from the system boundaries. Otherwise, a corrective factor can be defined and applied to collected data when site-specific data cannot be obtained and average distances from municipalities to landfills are used.
- PSR should better describe which operations have to be included in landfill construction and post-closure phases.

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